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Energy transformation in a free vortex

Ricketts, C. J.; Genta, John L.

Rensselaer Polytechnic Institute

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ENERGY TRANSFORMATION
IN A FREE VORTEX.

BY

C. J. RICKETTS

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Thesis
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ENERGY TRANSFORMATION IN A FREE VORTEX

A graduate thesis done in the
Mechanical Engineering Department
February - June 1947
at
RENSSELAER POLYTECHNIC INSTITUTE
TROY, NEW YORK

by

LT. COMDR. C.J.RICKETTS U.S.N.
LT. COMDR. J.L.GENTA U.S.N.

OBJECT OF INVESTIGATION

At the close of World War II, Allied scientists screening German technical papers reported the results of an experiment performed on basically a free vortex. This experiment was carried on by a German physicist, Rudolph Hilsch, in which he reported wide variations in total temperatures. This phenomena of total temperature variations is not in accord with classical free vortex theory.

The primary endeavor in this investigation was to design apparatus with which to attempt a reproduction of Hilsch's results. It was desired to have this design of such proportions and flexibility that a fundamental study of this phenomena could be carried out. Furthermore, with results obtained in experimentation a comparison could be made between these results and the prediction of classical free vortex theory.

APPARATUS

The first problem encountered was a method of producing a vortex of considerable strength. To produce a strong vortex, three nozzles designed for a Mach number of one, were spaced symmetrically around the periphery of a pipe in such positions that the centerlines of the nozzles would be parallel to the tangents of the pipe. This arrangement was desired in order that the flow would enter the pipe tangentially. The nozzles were designed with an arbitrary weight

30052

flow and pressure that was available from the laboratory compressor. A two inch diameter pipe was chosen since it was felt that this size pipe would be sufficient to produce a strong vortex and allow adequate instrumentation. An arbitrary length of three feet of pipe was selected and the nozzles were placed two feet from one end, which would allow some degree of flexibility in that the vortex could travel different distances within the pipe. An end test plate with static pressure and thermocouple taps on the same radius was designed to be fitted to either end of the pipe. The end test plate had a small hole at the center of the plate to allow the air to discharge. Originally, it was felt that by placing discs of various diameters in the pipe on the opposite side of the nozzles with respect to the end test plate, a separation of flow could be effected; that is, the air at the periphery would be drawn off at one end of the pipe and the core air would be discharged through the end test plate at the other end of the pipe. However, it was found that sub-atmospheric pressures were developed at the core and consequently atmosphere air was drawn in through the end test plate with this configuration. This made it necessary to design a plug which would force the flow through the test plate. With flexibility of design in mind, the flow divider, and subsequently the plug, were attached to the end of a supported rod which would allow positioning at varying distances from the nozzles. A section of the two inch pipe at the nozzles was enclosed within a manifold which served as a receiver of the supply pressure from the compressor. To facilitate further instrumentation taps were drilled through the outside of the pipe between the nozzles and the end test plate. A Bourdon Pressure Gage was located on the manifold. During the course of experimentation it was desired to obtain data in close to the nozzles. A plug was adapted to take total temperature, total pressure, and static pressure on the same radius. See Plates I, II, III, and IV.

An adaptation of a vortex valve designed by Professor Neil P. Bailey, head of the Mechanical Engineering Department of Rensselaer Polytechnic Institute, was used which permitted better instrumentation of the core phenomenom. The essential difference in the apparatus was the method in which the vortex was induced. The vanes were set at an angle of ten degrees with the tangent, and air from a receiver was directed through the vanes around the periphery of pipe. Static pressure taps were located on the back plate to which the vanes were attached. This apparatus was mounted on a lathe bed, which made it possible to rigidly mount and center precisely a thermocouple and pressure tubes. It was found that when making center traverses, it was absolutely necessary to stay at the center of the pipe, since any deviation from the center placed the instrument in the whirl of the vortex, causing it to vibrate violently.

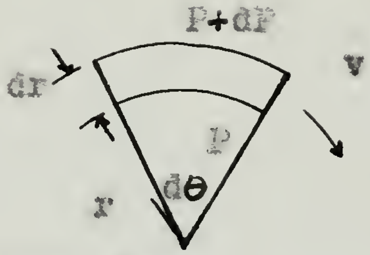
The thermocouples used in this investigation were shielded Chromel vs Alumel. For the nozzle induced vortex, the total pressure plug adapter was designed by means of a packing nut so that an impact tube could be rotated for the maximum pressure reading. See Plate IV.

PRESENT DAY FREE VORTEX THEORY

Present day free vortex theory is based on the following assumptions:

1. Constant total energy.
2. Reversibility.
3. Centrifugal forces are balanced by a radical pressure gradient.

With the foregoing assumptions and for the case of a compressible medium with no radial flow, a free vortex can be shown to be characterized by vr = constant.



A force balance gives

$$\rho\, r\,d\theta\,dr\,\frac{v^2}{r} = r\,d\theta\,dP \quad \text{-------------------------}(1)$$

From the general energy equation, the statement that the total energy is constant is,

$$\frac{R}{J}\,\frac{\gamma}{(\gamma-1)}\,dT+\frac{1}{Jg}\,v\,dv = 0 \quad \text{-------------------}(2)$$

For a gas,

$$\rho = \frac{P}{gRT} \quad \text{-------------------------------}(3)$$

Also, for a reversible change,

$$\frac{(\gamma-1)}{\gamma}\frac{dp}{P} = \frac{dT}{T} \qquad \text{------------------------------(4)}$$

Combining (1) with (3)

$$dP = \frac{P}{gRT}\frac{v^2}{r}\,dr \qquad \text{---------------------------(5)}$$

Eliminating (dT) between (2) and (4)

$$dT = \frac{T(\gamma-1)}{\gamma}\frac{dP}{P} = -\frac{(\gamma-1)}{\gamma}\frac{vdv}{Rg} \qquad \text{---------------(6)}$$

Solving (6) for $\frac{dP}{P}$

$$\frac{dP}{P} = \frac{-vdv}{RgT} \qquad \text{---------------------------------(7)}$$

Solving (7) and (1)

$$\frac{dP}{P} = \frac{v^2dr}{gRTr} = \frac{-vdv}{RgT} \qquad \text{-------------------------(8)}$$

Equation (8) says

$$\frac{dr}{r} = \frac{-dv}{v} \qquad \text{-----------------------------------(9)}$$

or that

$$vr = \text{constant} \qquad \text{----------------------------(10)}$$

At the center when v = 0, equation (10) inplies that the velocity is infinite and from the equation

$$Po/P = \left[1+\frac{\gamma-1}{2}\frac{v^2}{\gamma gRT}\right]^{\frac{\gamma}{\gamma-1}} *$$

a pressure of absolute zero is demanded at the center.

---

* This equation taken from "Thermodynamics of Air at High Velocities" by Neil P. Bailey

DISCUSSION OF RESULTS

Preliminary investigations with various diameter flow dividers, revealed sub-atmospheric pressures at the center of the end test plate. This meant that the flow was not discharging through the half inch diameter exit at the end plate, and necessitated designing a snug fitting plug which could be positioned at the nozzles, thus forcing the flow to discharge through the end test plate. With the plug in position, thermocouple probes at the end test plate revealed a drop in total temperature from the outer diameter to the center of considerable magnitude, which was not obtained with the original design idea of flow division. In an effort to obtain a picture of the temperature and pressure variation along the length of the pipe, taps were drilled, through which measurements could be taken. With this set-up, data for curves number 1 and number 2 were obtained. A diameter traverse showed a small drop in total temperature at the outer radii, with a much greater drop in towards the center. The lowest temperature was at the center of the pipe. Diameter traverses at the other taps gave the same general total temperature trend. A significant temperature difference between taps at the same outer radii was noted, with the difference becoming less in towards the center. For an incoming total temperature of 101° F, the center total temperature varied from 73° F at the outer tap, to 68° F at the tap nearest the nozzles. It is of interest to note that the total temperature at the outer-most radius varies from 8° F above the incoming temperature at the outer tap, to 11° F below the incoming temperature at the tap nearest the nozzles. It must be pointed out that with this method of instrumentation in which the thermocouple is traversed through the flow, the phenomena under investigation is altered by the presence of the thermocouple. This was very obvious, evidenced by a distinct change in sound as the traverse was taken. This probably accounts for the unsymmetrical readings. However, it is felt that this would indicate the general trend, but would limit the reliability of the results. Attempts made to check these readings by probing through the end test plate along the length of pipe were unsuccessful, due to the vibrations set up by the whirl of the vortex.

A possible explanation of this total temperature variation might be given by considering that at any time a velocity or temperature gradient exists in an actual gas, the "transport phenomena" of viscosity and thermal conduction are present. As the air first leaves the nozzles and spirals in toward the center of the pipe, which was orginally at atmospheric pressure, a velocity gradient is established. Due to this velocity gradient a viscous force exists. This viscous force is a function of the change of momentum which takes place between adjacent layers of air traveling at different velocities. Therefore, work is done and energy can be thought of as being transported from the layer of higher velocity air. By the mechanism of thermal conduction

a part of this energy transferred can be thought of as appearing in the form of thermal energy in the adjacent layer. Since total temperature is a measure of the energy of a system, and the layer of air traveling at the higher velocity has given up some of its energy, it follows that the total temperature of this layer would be reduced. A fair assumption would be to consider that the radial forces are balanced, which would discount the effect of mass diffusion. If the velocity is increasing in toward the center of the vortex, the over-all effect of the viscous action would become greater, which accounts for the lowest temperature occuring at the center of the pipe. As the flow travels down the length of pipe, and as long as the viscous forces continue to act, the total temperature at the center would decrease and the total temperature at the outer radii would increase. With more viscous work being done at the center, the velocity would decrease faster at the center than at the outer radii. If an ideal case is considered with no friction from the pipe wall, and the viscous forces are dissipated, it is conceivable that a state approaching constant angular velocity would result, in which there would be no static temperature gradient. However, this would still allow the existence of the total temperature gradient. Actually, the friction of the wall will decrease the velocity at the outer radii, thereby raising the static temperature at those radii. As this process continues thermal energy would be transported back to the center.

Eventually, the angular velocity would be reduced to zero, at which time a total temperature gradient would no longer exist. This would represent the life cycle of the vortex.

From the plot of curve number 2, it is noted that the lowest total temperature was not measured at the same distance from the nozzles as was the highest total temperature. This would seem to contradict the theory as presented, in that the theory would call for the maximum and minimum total temperature to occur at the same distance from the nozzles. Upon investigation, sub-atmospheric pressures were detected at the exit of the end test plate. This would mean that atmospheric air was being pumped back into the pipe, and, consequently, the thermocouple would read a value that was a function of the mixture of the cold air and the warm room air at the center of the pipe. The better instrumentation possibilities available with the vane induced vortex apparatus allowed an investigation of this effect. These results are given in the data contained in table number 9 and plotted as curve number 9. In an effort to determine how far back into the center of the pipe room air was being pumped, three types of pressure tubes were designed. With these pressure tubes it was felt that the direction of the air flow at the center of the pipe could be determined. If a center traverse were taken with an open-ended tube, and the flow were discharging out of the center of the pipe, a reading approaching total pressure would be obtained. However, if the flow were reversed, as would be the case in a pumping action, the reading obtained would approach a value less than static. If these measurements are compared with the measurements taken with an open-ended tube with a 180° bend, the direction of the flow is indicated. A static pressure center traverse was also taken to confirm the conclusions. It was confirmed that a reversal of flow direction was occurring at the center with room air being pumped into the center of the pipe. With the available tubing material, even though the tubes were firmly anchored and accurately centered, it was not possible to investigate the pumping effect beyond a distance of three inches from the discharge end of the pipe. Again, instrumentation difficulties were caused by the whirl of the vortex. The effect of this pumping on the total temperature at the center of the pipe was determined by placing a shield near the exit which prevented the pumping action. The shield was free to assume an equilibrium position, and thus it was felt that its only effect was to stop the pumping action. On the first attempt to study this effect, the thermocouple did not fit snugly in the hole at the center of the shield, and the shape of the total temperature center traverse curve was not affected by the presence of the shield. A shield then was tried in which the thermocouple did fit snugly, and this time the lowest total temperature recorded was not affected appreciably; but this low temperature existed for a greater distance, and the temperature did not increase to as high an exit value as in the case without a shield. These results are given in table number 8 and plotted as curve number 8. The exit total temperature without the shield was 74° F and with the shield the total temperature was 53° F. Therefore, it seems reasonable to assume that pumping action could account for the apparent contradiction to the theory as presented; that is, without this pumping action, the center traverse plotted on curve number 2 would have decreased instead of increased.

From the theory as presented the lowest temperature detected would be a function of the intensity of the vortex. If the incoming total pressure is reduced the entering Mach number will be reduced. Hence, the strength of the vortex will decrease. This was substantiated by varying the total pressure forming the vane-induced vortex. These results are given in table number 6 and plotted as curve number 6. With an incoming total pressure of 51.6" Hg absolute, the lowest total temperature detected was 32° F, while with an incoming total pressure of 40.7" Hg absolute, the lowest total temperature was 65° F.

Static pressure measurements were taken at the vane plate for different incoming total pressures. It is interesting to note their variations, but this data appears to be of no particular use at this time. These results are given in table number 7 and plotted as curve number 7 for possible future use.

It would be of great interest to know the Mach number in a vortex at the different radii as it develops, travels down the pipe, and as it begins to dissipate. It is realized that an accurate determination would be most difficult because of the nature of the flow and its accompanying instrumentation problems. As was pointed out previously, the slightest probing altered the nature of the flow, evidenced by a distinct change in sound. Furthermore, any measurements obtained would be some function of the vortex flow and the flow component as the vortex traveled down the pipe. With these difficulties in mind it was felt that perhaps a trend of the Mach number versus radius could be found. A diameter traverse was made on the discharge side of the nozzles with an impact tube, and the impact tube was rotated until a maximum total pressure reading was obtained. Static pressure was determined by rotating the impact tube until the minimum reading was obtained. It is fully realized that these pressure readings would be considerably lower than the actual static pressures, due to the wake around the impact tube caused by the flow. The results of this investigation are given as a part of table 5 and plotted as one of the curves numbered 5. The data is given only for possible future reference.

During the course of this investigation, a ring formation was noted on the seal used to force the flow to discharge through the end test plate. The ring was formed by the oil present in the supply air. In present day free vortex theory an infinite velocity is implied at the center of the free vortex. If the flow velocity could approach infinity at the center, it would first have to go through a Mach number of one.

There is no apparent mechanism in a free vortex that would allow the flow to exceed sonic velocity. With this in mind it was thought that possibly the ring represented the point at which there was a discontinuity of flow, and where the Mach number of the vortex could not exceed unity. This ring is shown in a photograph on page 25. Again, instrumentation presented a problem, but a re-design of the seal plug on which the ring appeared was possible. This would not disrupt the flow to the extent of that resulting from a diameter traverse. This re-design is shown on plate number 4. To study this ring formation the following procedure was used. The seal plug was removed and covered with a mixture of bone black and oil, repositioned, and the incoming total pressure raised to a particular value. The length of time that the pressure was maintained was varied. Then the pressure valve was turned off, the seal plug removed, and the ring formation observed. By this procedure it was found that the ring formation first appeared at .5 inches from the nozzles and could not be produced beyond 1.25 inches from the nozzles. The diameter of the ring varied in size, depending upon the distance the seal plug was away from the nozzles. The ring diameter at .5 inches from the nozzles was 1.375 inches, and the ring diameter at 1.25 inches from the nozzles was .874 inches. This data is given in table number 4 and plotted as curve number 4. The position of the seal plug was varied until the diameter of the ring was such that measurements of total and static pressures could be made at the ring and on either side of the ring. It must be pointed out that a difference of flow pattern exists, in that the flow set-up is not on the discharge side of the nozzles, as has been the case in all previous investigations. Consequently, no justification is at hand for predicting that the same conditions exist on the discharge side as were present to produce the ring.

Velocity determinations did not support the idea that a Mach number of one occurred at the ring. In fact a complete reversal of trend was shown with the velocity decreasing from the outer radii to the ring, as is seen from data given in table 5 and plotted as curve 5.

It is felt that some correlation may exist between the ring and the core of free vortices produced by nature. Cores, or calm areas, are known to exist in tornadoes, whirl pools, and hurricanes; but their velocity gradients increase towards the center. No further explanation is offered at this time.

CONCLUSIONS

Present day free vortex theory did not predict the results of this investigation. When one considers the assumptions upon which present day free vortex theory is based, some degree of variance might well be expected, but the magnitude of this variance is surprising.

In the present day theory reversibility, constant total energy and a radial force balance are assumed; but the "transport phenomena" of viscosity and thermal conduction are neglected. Even if the process is not considered reversible, and the total energy remains constant, but the two "transport phenomena" are not considered, no change of total temperature would be expected between layers of air in a free vortex. Considering the effect of the two "transport phenomena" of viscosity and thermal conduction, a qualitative analysis which accounts for the variation of total temperature has been presented in the discussion of this thesis.

SUGGESTIONS FOR FUTURE INVESTIGATION

A primary consideration in regard to future study should be the problem of instrumentation. As was pointed out, diameter traverses cause a considerable change in the flow being studied. Center line traverses did not appear to alter the flow appreciably, and consequently, the results of a center traverse are felt to be more reliable. It is strongly recommended that some method of firmly anchoring and precisely centering any probing instrument be used to decrease the effect of the vibrations caused by the whirl.

The length of pipe necessary to reach the maximum total temperature and the minimum total temperature should be determined. A further check on the theory would be had if the maximum and minimum occurred at the same distance along the pipe.

It is felt that if the Mach number at different radii of the vortex could be established, considerable light would be thrown on the subject.

8082

Before any definite conclusions can be drawn, the overall effect of the pumping action should be clearly determined.

It was found that by sealing the exit of the end test plate, thus forcing the entire flow at the opposite end, free of any restrictions, the outside temperature on the end test plate side of the nozzles became noticeably warmer than under the set-up by which data was obtained for curve number 1. The results of a diameter traverse are given in table number 2 and plotted as curve number 3. It is striking to note that at each radii, the total temperatures were above the incoming total temperatures entering the pipe. Time did not permit a redesign of the apparatus which would have been necessary to determine the factors producing this effect.

TABLE NO. 1 and NO. 2

Pipe sealed at nozzles causing flow to
discharge through test plate.

Tap No. 1 - 10.81 inches from nozzles
Tap No. 2 - 9.19 inches from nozzles
Tap No. 3 - 6.31 inches from nozzles
Tap No. 4 - 3.63 inches from nozzles

Manifold Pressure 60 psi Gage
Manifold Total Temp. 101°F

Distance Along Diam. of Pipe-Inches	Tap #1 T_o °F	Tap #2 T_o °F	Tap #3 T_o °F	Tap #4 T_o °F
0.0938	109.0	107.0	94.5	90.0
0.344	107.0	104.0	93.0	83.0
0.594	104.0	103.0	93.0	85.0
0.844	95.0	91.5	90.0	82.5
1.094	73.5	74.0	68.0	66.0
1.344	96.0	95.5	94.5	90.0
1.594	103.0	101.0	98.5	89.5
1.844	102.0	100.0	98.5	91.0
2.060	104.0	103.0	99.5	95.5

TEST PLATE DATA

Test hole No. 1	.61	inches along diameter of pipe
Test hole No. 2	.35	inches along diameter of pipe
Test hole No. 3	.08	inches along diameter of pipe

Note: Test Plate is 12 inches from nozzles.

Distance along diam.of pipe - inches	.08	.35	.61	Center
Total Temp. °F	109	105	96	46

Test Plate on opposite end of pipe-Distance from nozzles 24 in.

Distance along diam.of pipe - inches	.08	.35	.61	Center
Total Temp. °F	93.5	90	85.5	34

TABLE NO. 3

Test Plate sealed causing flow to
discharge at opposite end.

Tap No. 1 - 10.81 inches from the nozzles
Tap No. 3 - 6.51 inches from the nozzles

Manifold Pressure 60 psi Gage
Manifold Total Temp. 96.5° F

Distance Along Diam. of pipe - inches	Tap #1 T_o °F	Tap #3 T_o °F
0.0938	135.0	128.8
0.344	134.4	126.0
0.594	133.3	124.0
0.844	129.5	121.0
1.094	126.0	118.8
1.344	128.2	119.7
1.594	132.7	122.0
1.844	132.7	125.0
2.060	133.0	126.5

TABLE NO. 4

RING FORMATION DATA*

Test Plate in position opposite end
sealed off at varying positions.

Bone Black and Oil Mixture used
as tracing medium.

Manifold Pressure 60 psi Gage

Distance of Seal away from nozzles in inches	Diameter of ring - inches	Remarks
0	-	No ring
.125	-	No ring
.25	-	No ring
.375	-	No ring
.50	1.375	
.625	1.375	
.75	1.312	
.875	1.25	
1.000	1.065	
1.125	1.000	
1.25	0.875	Ring unstable
1.375	0.000	No ring appeared
1.875	0.000	No ring

* See photograph in discussion

TABLE NO. 5

Nozzle induced ring formation determination
of Mach Number with respect to ring.

Data obtained from instrumentation set-up on disc where ring was formed. The disc was used to force the entire flow to discharge thru the end Test Plate.

Distance Along Radius - Inches	Ps Abs. "Hg	P_o Abs. "Hg	P_o/P_s	M
.9	53.3	63.8	1.195	.525
.74	51.2	58.7	1.148	.450
.64	50.1	54.3	1.063	.300
.54	49.1	51.0	1.040	.237
.40	49.6	49.9	1.007	.080

Determination of Mach Number at 6.3 inches
away from nozzles.

Data obtained on the discharge or end Test
Plate side of the nozzles.

Distance Along Radius - Inches	Ps Abs. "Hg	P_o Abs. "Hg	P_o/P_s	M
.936	50.8	56.8	1.12	.406
.686	48.6	54.0	1.10	.372
.436	46.5	53.1	1.14	.437
.189	36.1	46.1	1.28	.605
0	-	-	1.83	.97

At $r = 0$ an average of three readings was taken.

TABLE NO. 6 and NO. 7

Measurements taken without exit shield.

Barometer Reading 30.10 "Hg.

Pressure Ratio Available
For M = .810

P_2	54.7 "Hg Abs.
P_1-P_2	33.1 "Water
P_3	35.6 "Hg Abs.
P_4	26.9 "Hg Abs.
P_5	28.2 "Hg Abs.
P_6	28.9 "Hg Abs.

Incoming Total Temp. 96°F

X inches	T_o °F
0	30
.5	28
1.0	28
1.5	30
2.0	30
2.5	32
3.0	32.5
3.5	33
4.0	37.5
4.5	43
5.0	51.5
5.5	65
6.0	74

Pressure Ratio Available
For M = .751

P_2	51.6 "Hg Abs.
P_1-P_2	29.6 "Water
P_3	34.9 "Hg Abs.
P_4	27.3 "Hg Abs.
P_5	28.4 "Hg Abs.
P_6	29.1 "Hg Abs.

Incoming Total Temp. 104°F

X inches	T_o °F
0	40
.5	33
1.0	33
1.5	33
2.0	35
2.5	35
3.0	38
3.5	41
4.0	46
4.5	54
5.0	61
5.5	-
6.0	74

TABLE NO. 6 and NO. 7
(Cont'd.)

Pressure Ratio Available
For M = .676

P_2	45.3 "Hg Abs.
P_1-P_2	22.8 "Water
P_3	33.1 "Hg Abs.
P_4	27.5 "Hg Abs.
P_5	28.1 "Hg Abs.
P_6	28.5 "Hg Abs.

Incoming Total Temp. 105°F

X inches	T_o °F
0	60.5
.5	56.5
1.0	55
1.5	53
2.0	53
2.5	53
3.0	53
3.5	55
4.0	57
4.5	60
5.0	66.5
5.5	70.5
6.0	74

Pressure Ratio Available
For M = .548

P_2	40.7 "Hg Abs.
P_1-P_2	16.8 "Water
P_3	32.6 "Hg Abs.
P_4	28.9 "Hg Abs.
P_5	29.3 "Hg Abs.
P_6	29.6 "Hg Abs.

Incoming Total Temp. 105°F

X inches	T_o °F
0	72
.5	67.5
1.0	67
1.5	66
2.0	65
2.5	65
3.0	65.5
3.5	67.5
4.0	69
4.5	72.5
5.0	76.5
5.5	78
6.0	78

TABLE NO. 8

VANE INDUCED VORTEX

Temperature traverse along center of pipe without and with shield over end of pipe.

Distance Along Pipe in Inches	Unshielded P_o = 51.6 "Hg Abs. (T_o)in = 104°F Total Temp °F	Shielded P_o = 52 "Hg Abs. (T_o)in = 103°F Total Temp °F
0	40.0	35.0
.50	33.0	32.0
1.00	33.0	31.0
1.50	33.0	31.0
2.00	35.0	31.0
2.50	35.0	32.5
3.00	36.0	32.0
3.50	41.0	35.0
4.00	46.0	35.0
4.50	54.0	36.0
5.00	61	39.5
5.50	-	43.5
6.00	74.0	53.0

TABLE NO. 9

VANE INDUCED VORTEX - No Shield

Pressure traverse along center of pipe

Three types of pressure tubes used.

1. Straight tube with open end.
2. A static pressure tube. Straight tube, closed end, pressure hole 3/4" from end.
3. A tube with a 180° bend, open end.

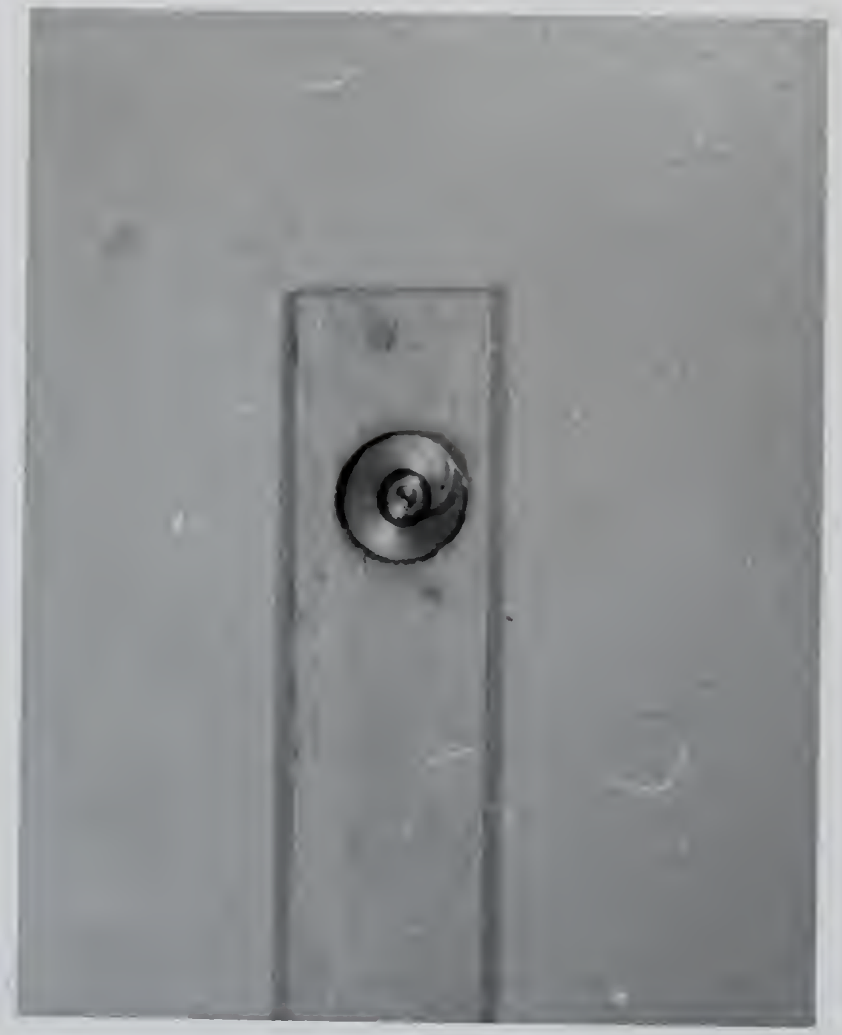
X = 0 at vanes

Distance Along Pipe - Inches X	Straight Pipe Open End "Hg Abs.	180° Bend in Pipe "Hg Abs.	Static Pressure Tube "Hg Abs.
6.0	28.3	29.1	28.4
5.5	26.1	28.1	27.5
5.0	25.7	27.1	26.3
4.5	24.9	26.3	25.7
4.0	24.3	25.9	25.3
3.5	23.9	25.5	24.5
3.0	23.7	24.5	24.1

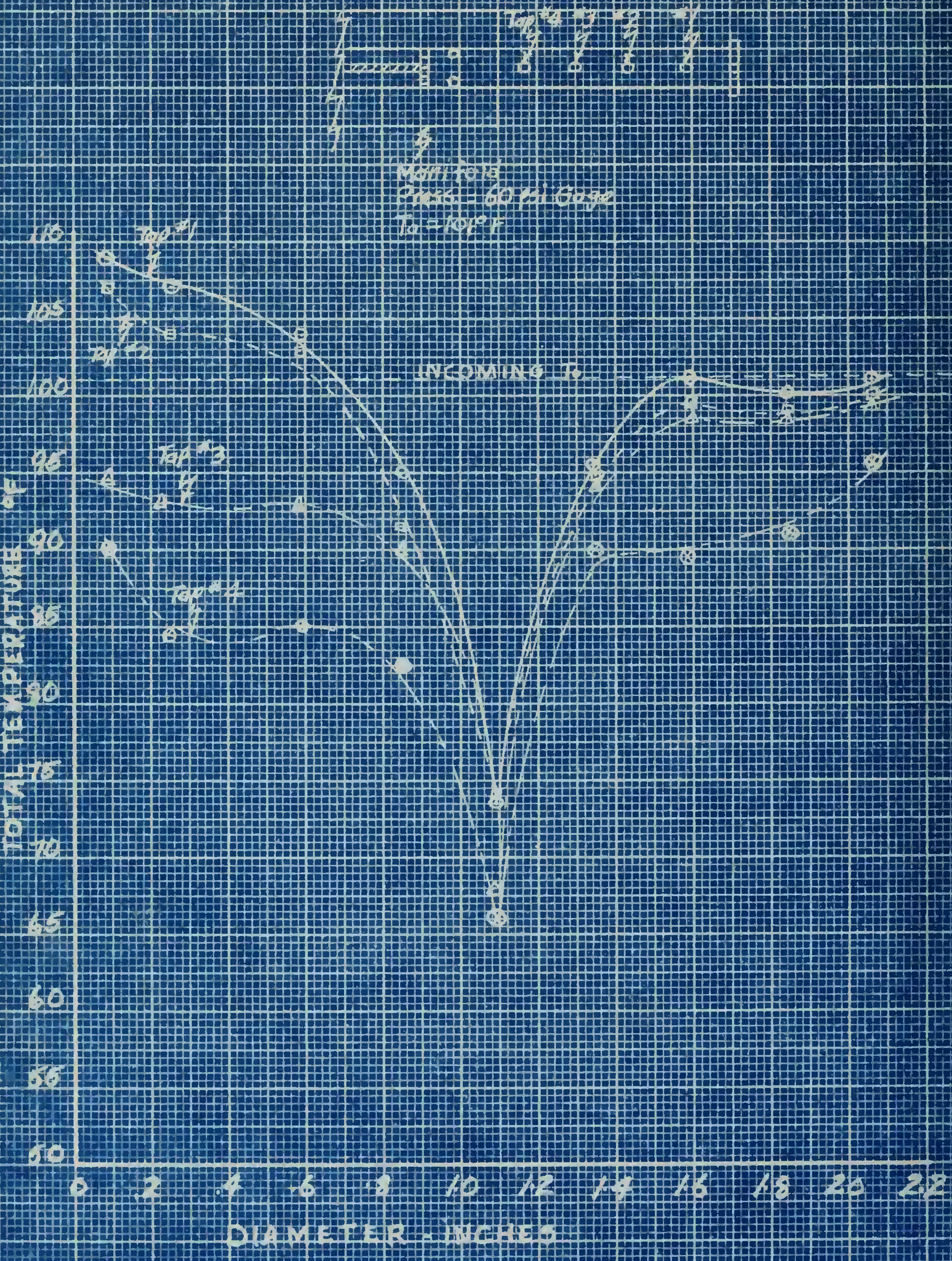
NOZZLE INDUCED RING FORMATION

This ring formed on disc used to seal off pipe forcing all the air to discharge thru Test Plate.

Distance from Nozzles	0.50	Inches
Diameter of Ring	1.375	Inches

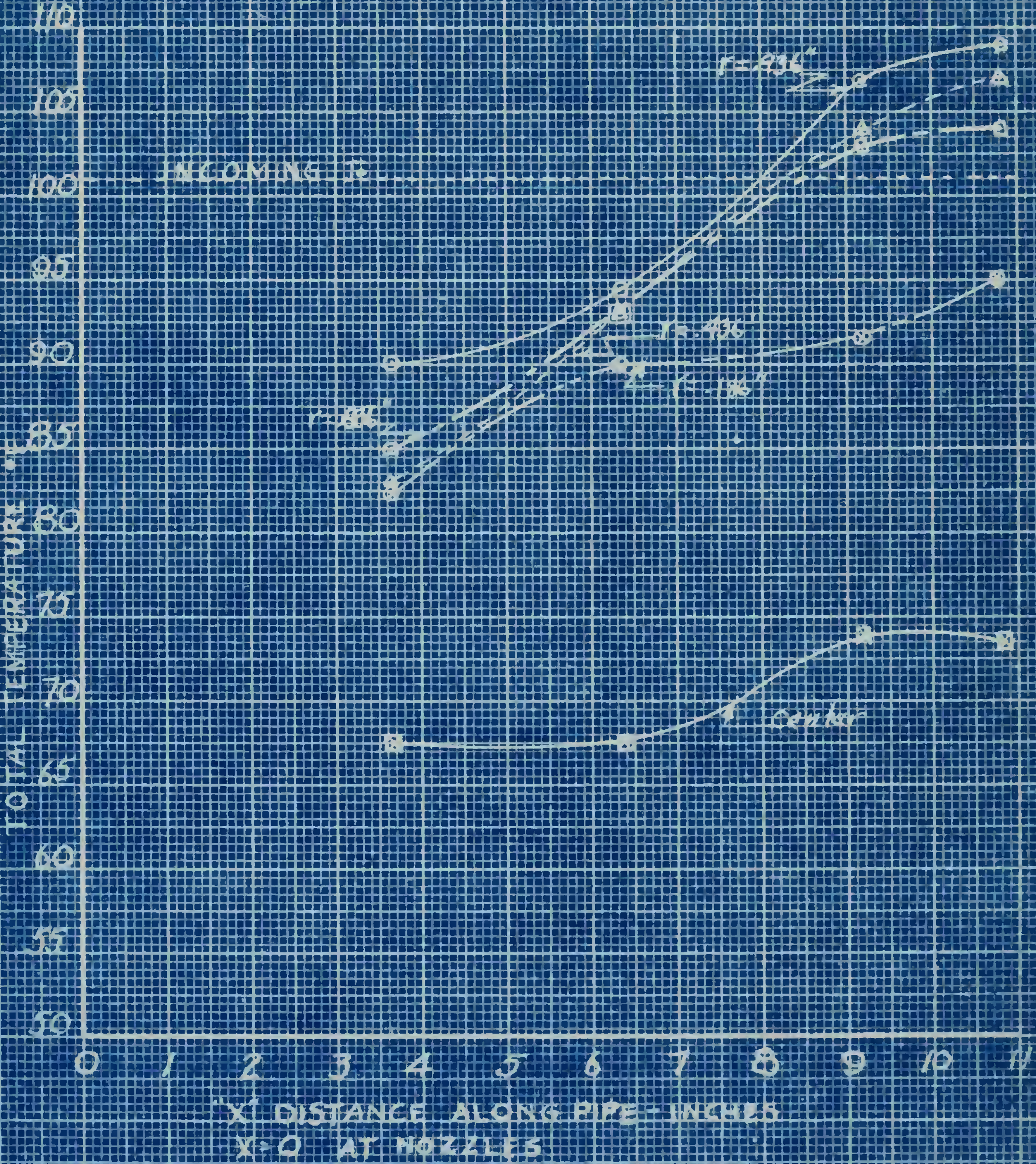


CURVE NO. 1
TOTAL TEMPERATURE
VS
DIAMETER TRAVERSE



GENTA AND RICKETTS

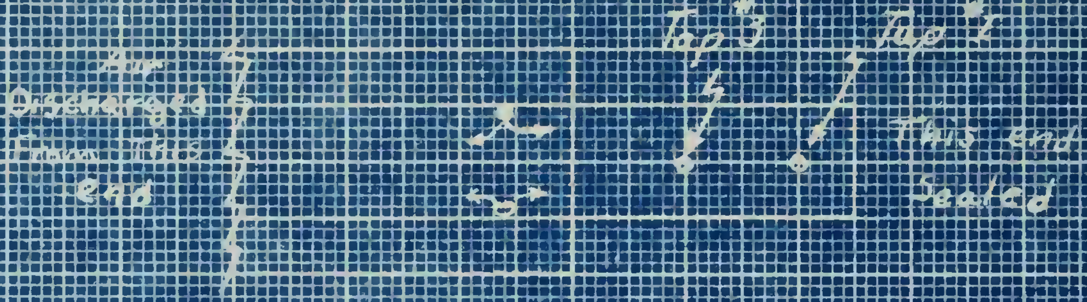
CURVE NO. 2
TOTAL TEMPERATURE
VS
DISTANCE ALONG PIPE AT DIFFERENT RADII
FOR NOZZLE INDUCED VORTEX

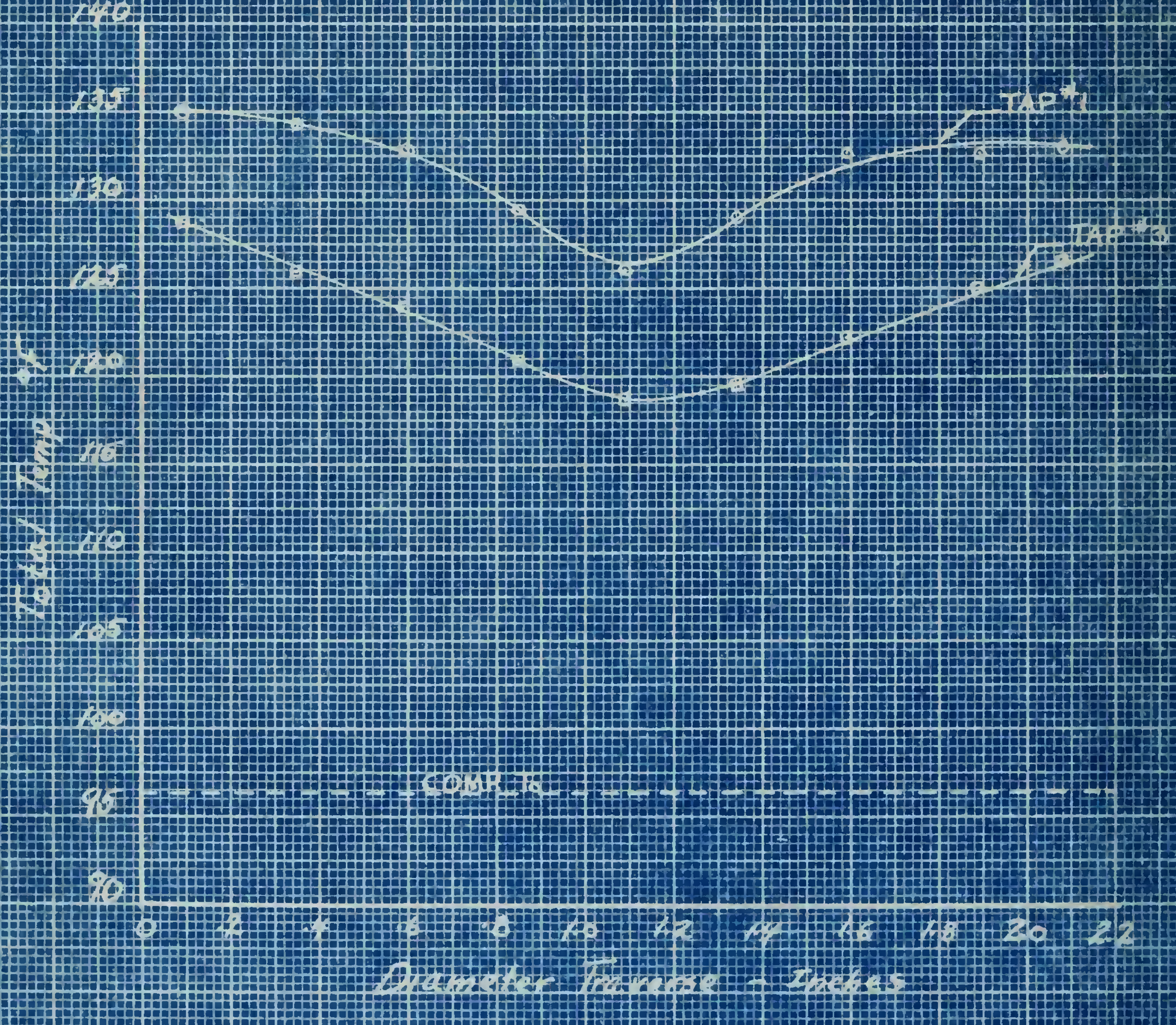


GENTA AND RICKETTS

TOTAL TEMPERATURE
VS.
DIAMETER TRAVERSE

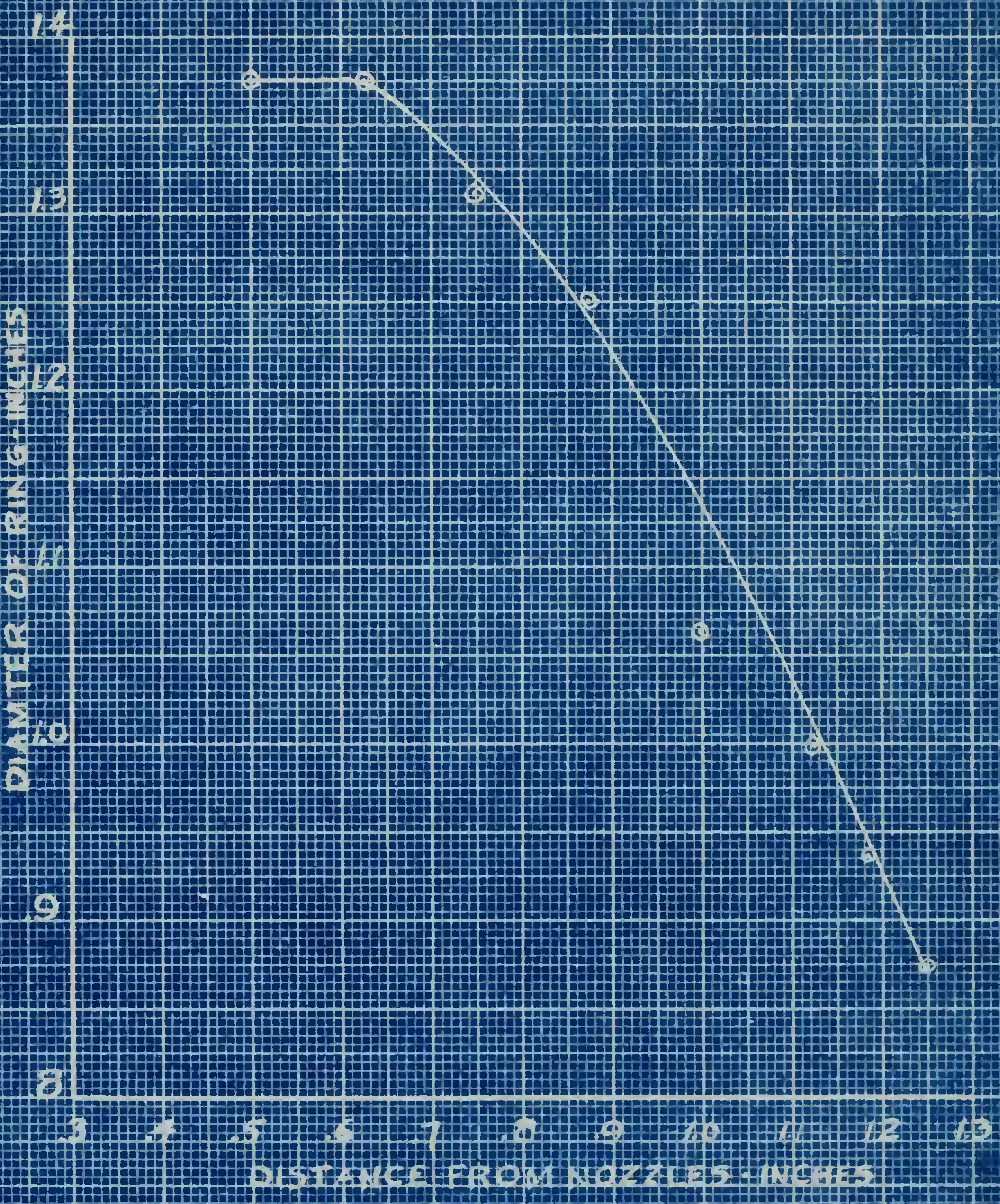
CURVE NO. 3





GENTA AND RICKETTS

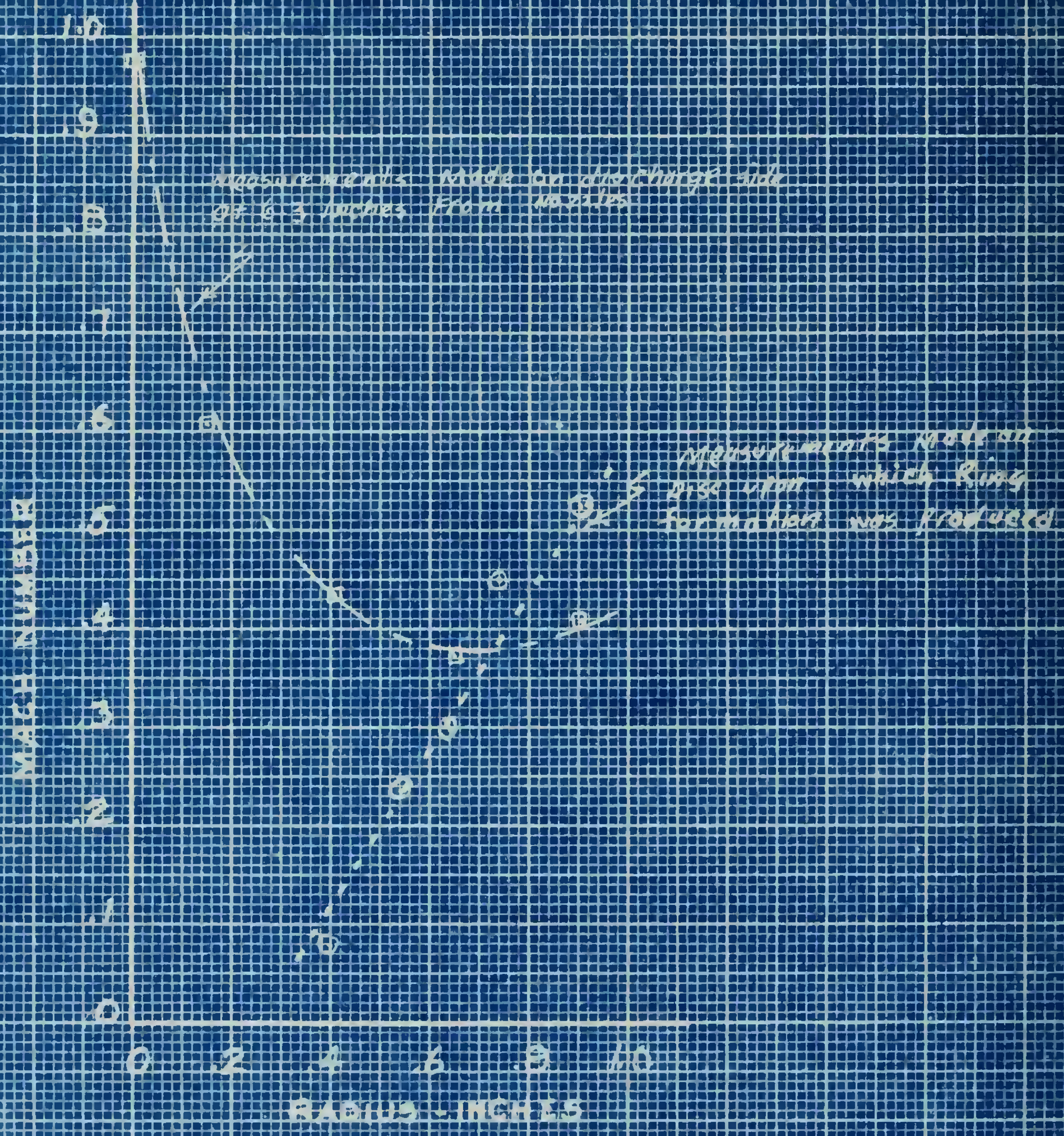
CURVE NO. 4
DIAMETER OF CORE
VS.
DISTANCE FROM NOZZLES



GENTA AND RICKETTS

CURVE NO. 5
NOZZLE INDUCED VORTEX

MACH NUMBER VS RADIUS



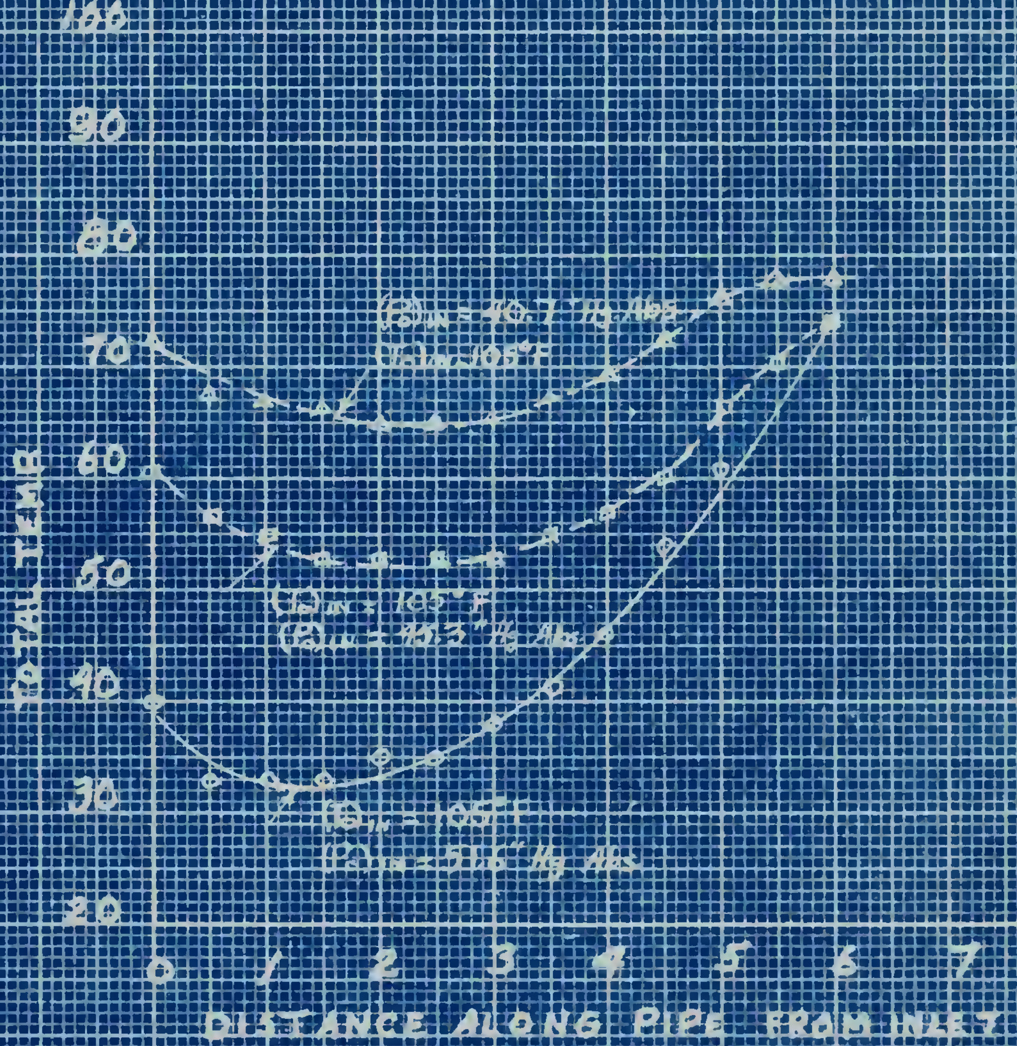
Measurements made on discharge side
of 6.3 inches from nozzles

Measurements made on
disc upon which Ring
formation was produced

GENTA AND RICKETTS

CURVE NO. 6
VANED INDUCED VORTEX - NO SHIELD

TOTAL TEMPERATURE CENTER TRAVERSE
VS
DISTANCE ALONG PIPE



GENTA AND RICKETTS

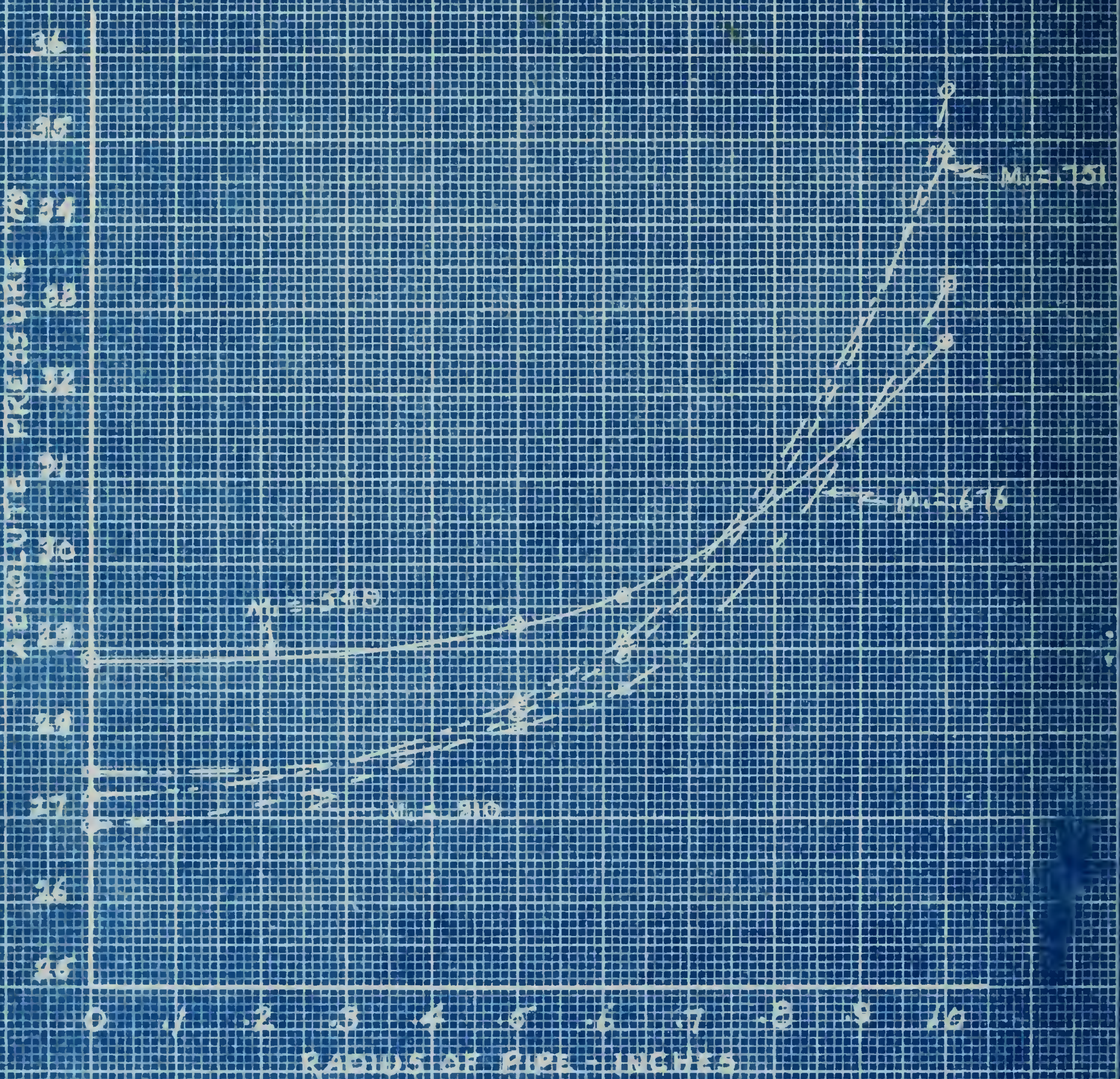
CURVE NO. 7

VANE INDUCED VORTEX - NO SHIELD

STATIC PRESSURE VS PIPE RADIUS

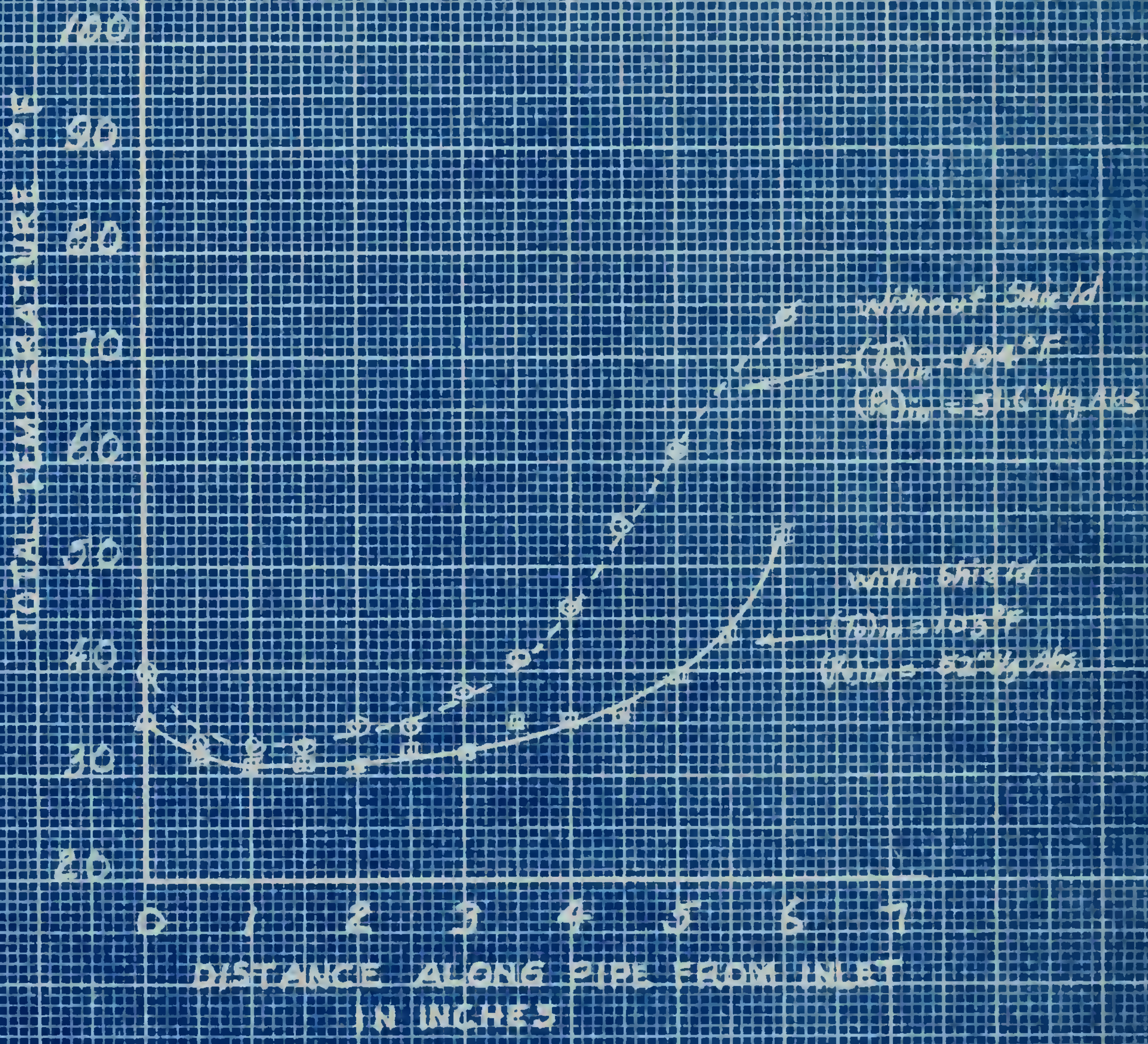
Taps Located on Vane Plate

M_1 is The Mach No. Leaving The Vanes



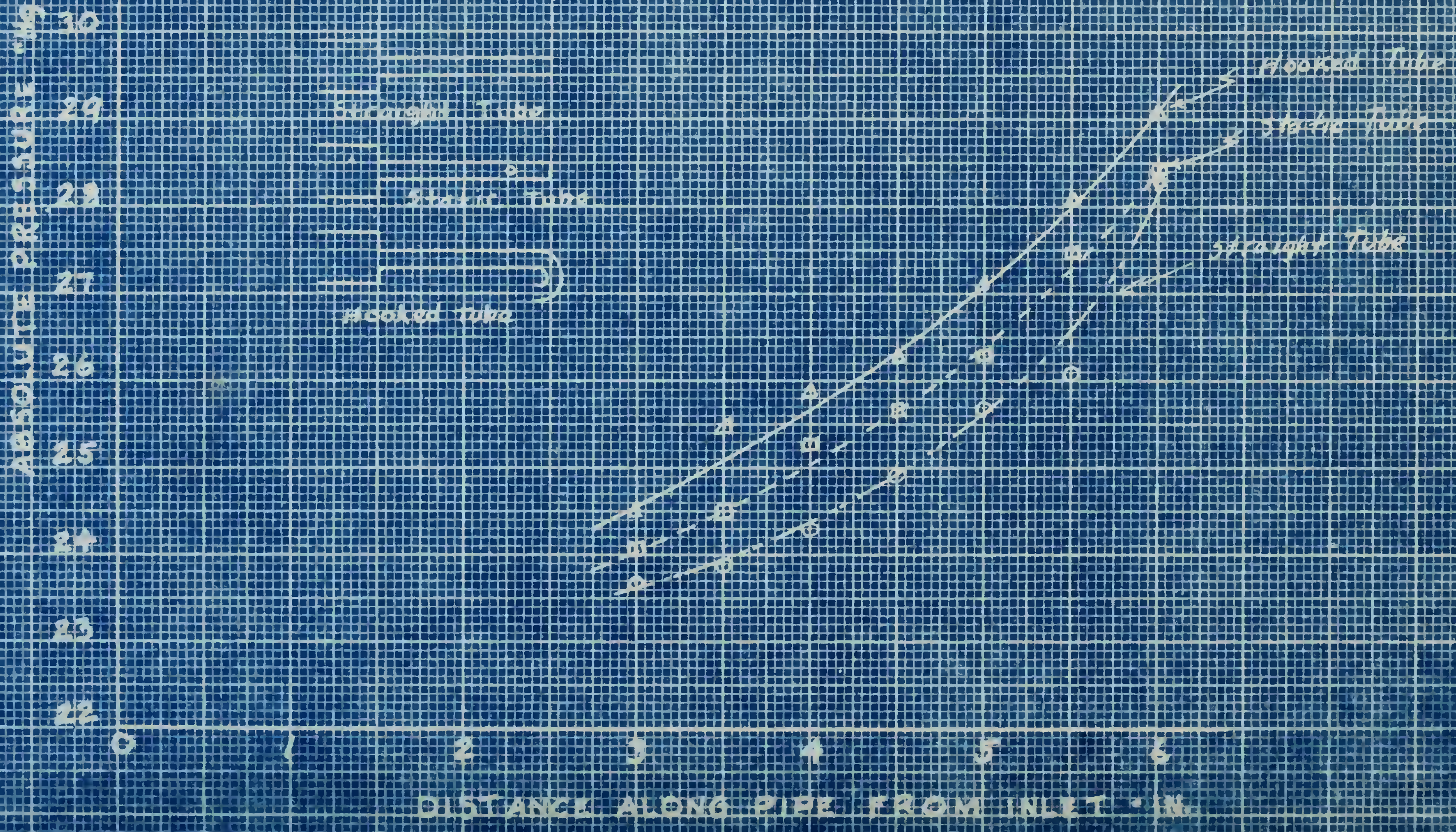
GENTA AND RICKETTS

CURVE NO. 8
VANE INDUCED VORTEX
TOTAL TEMPERATURE CENTER TRAVERSE
VS
DISTANCE ALONG PIPE

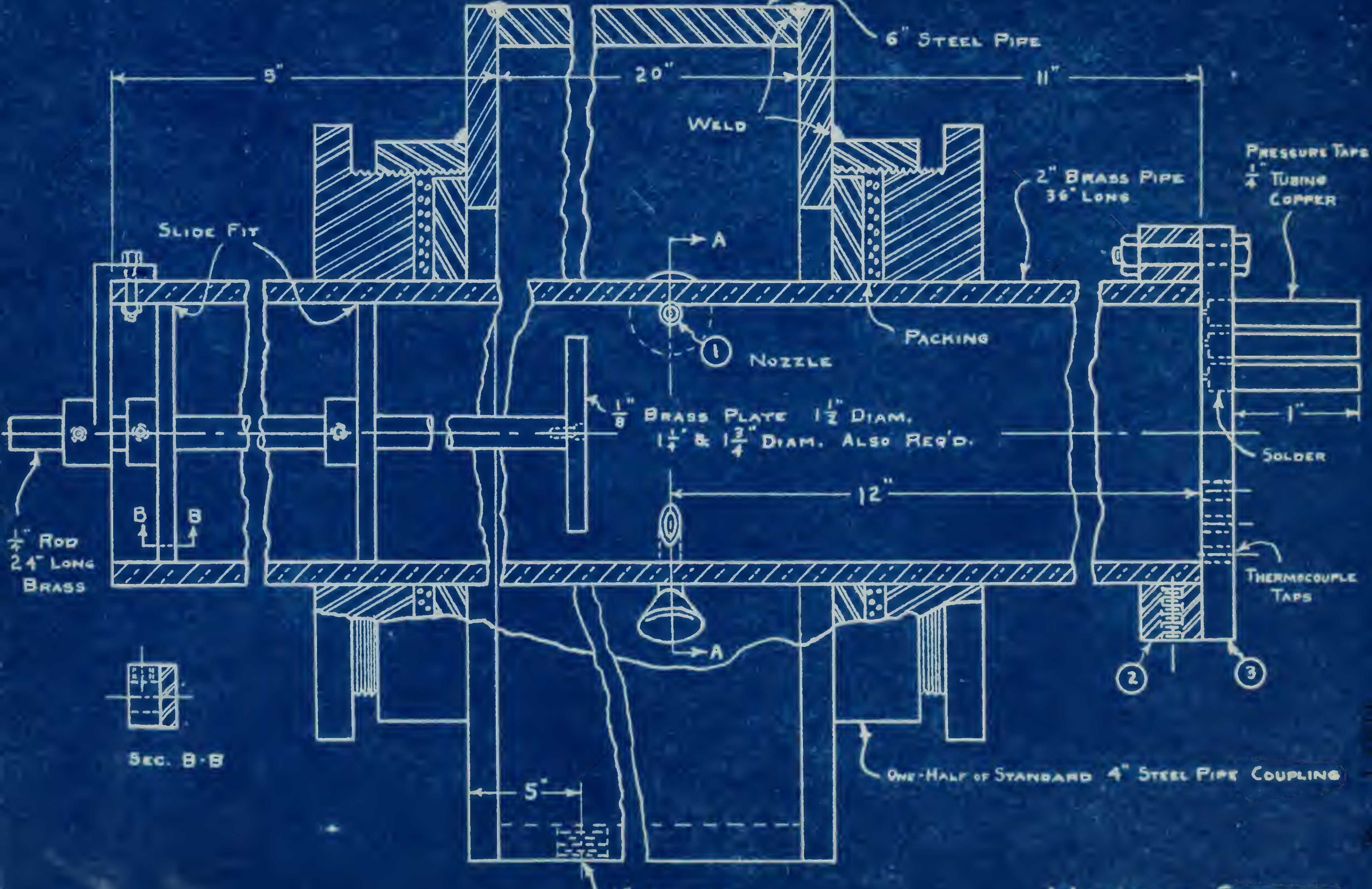


GENTA AND RICKETTS

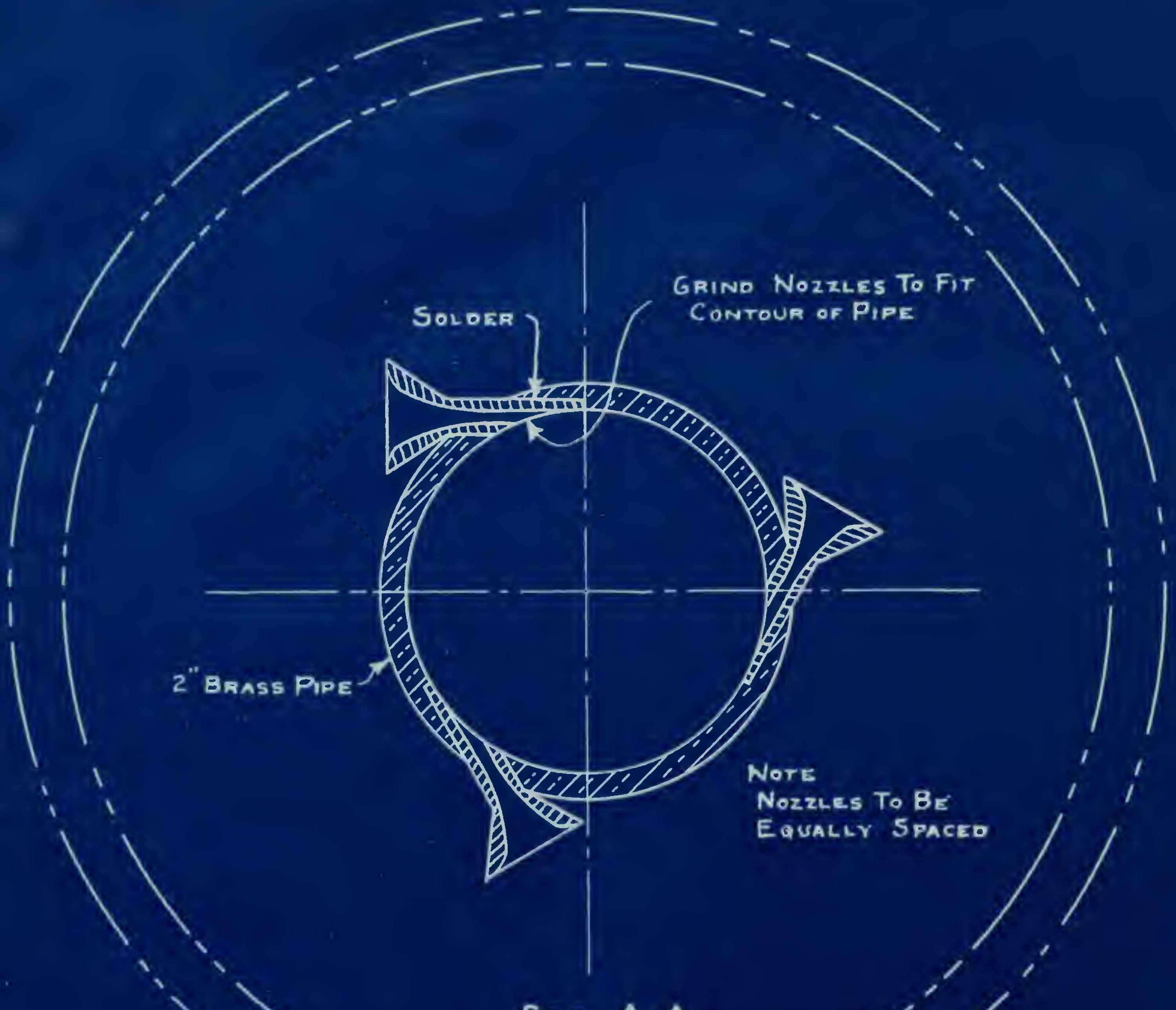
CURVE NO. 9
VANE INDUCED VORTEX - NO SHIELD
CENTER LINE PRESSURE TRAVERSE
VS.
DISTANCE ALONG PIPE



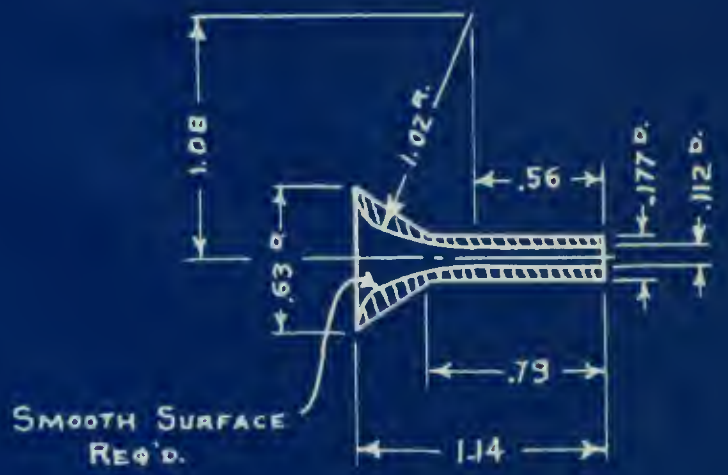
GENTA AND RICKETTS



MANIFOLD SECTION
SCALE – FULL



Sec. A-A



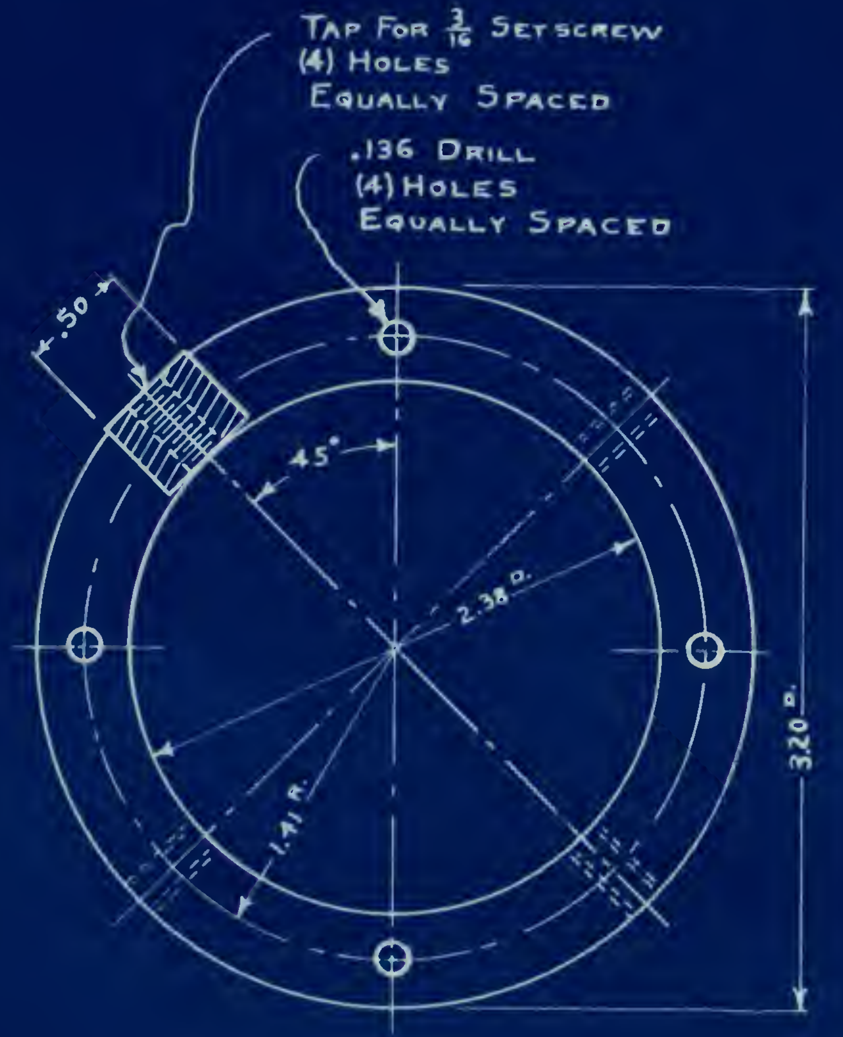
①

Nozzle
Brass
(3) Req'd.

Throat Area of Nozzle .00983 Sq. In.

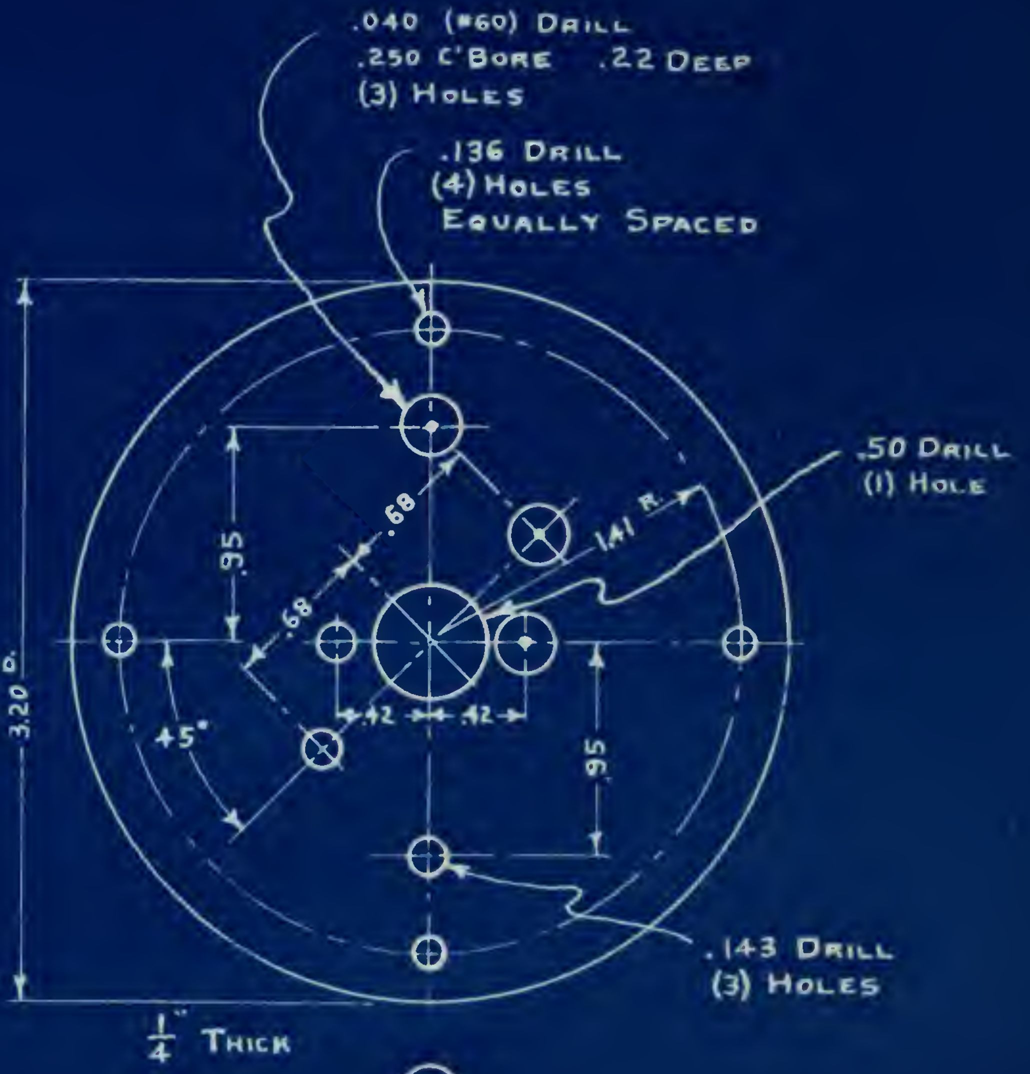
Nozzle Assembly & Detail

Scale - Full



②

COLLAR
BRASS
(1) REQ'D



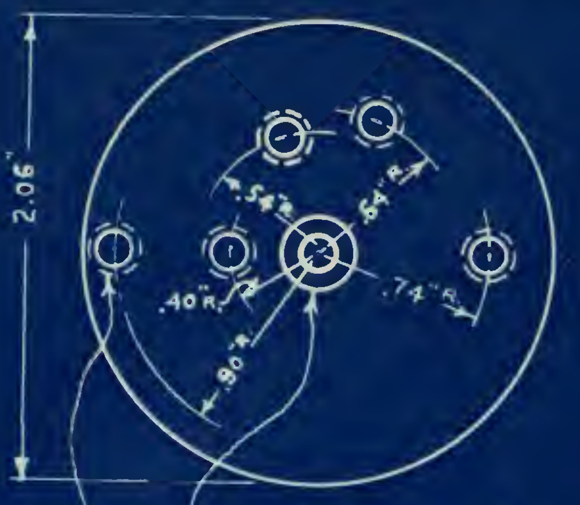
③

END PLATE
BRASS
(1) REQ'D.

COLLAR & END PLATE DETAIL

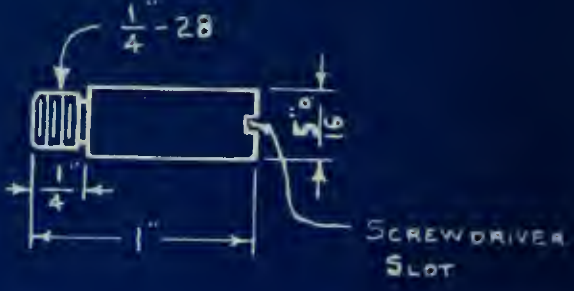
SCALE – FULL

RING FORMATION TEST PLATE



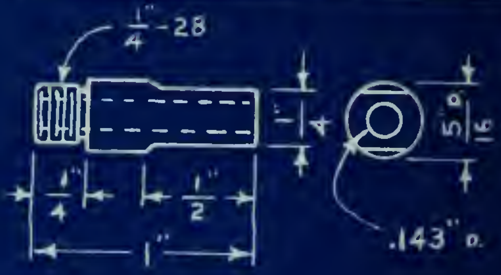
DRILL & C'SK FOR $\frac{3}{16}$" MCH. SCREW
$\frac{1}{4}$"-28 (5) HOLES
BRASS $\frac{1}{4}$" THICK

PLUG



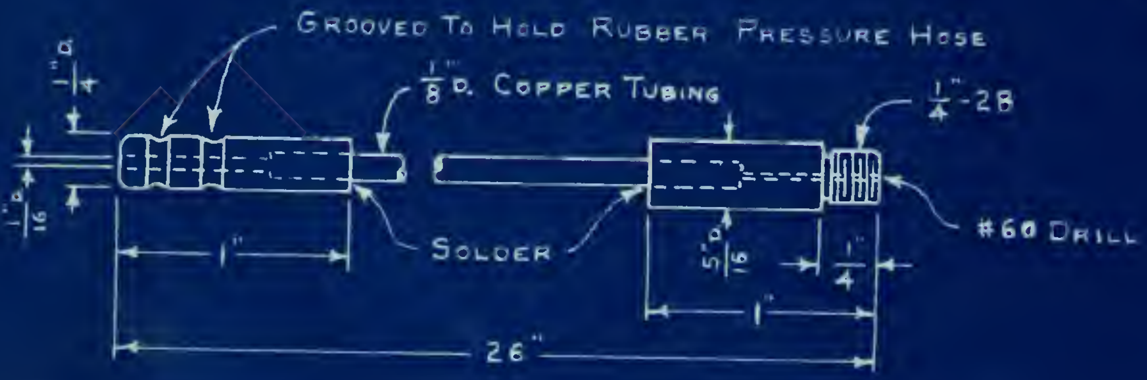
BRASS (5) REQ'D.

THERMOCOUPLE ADAPTER

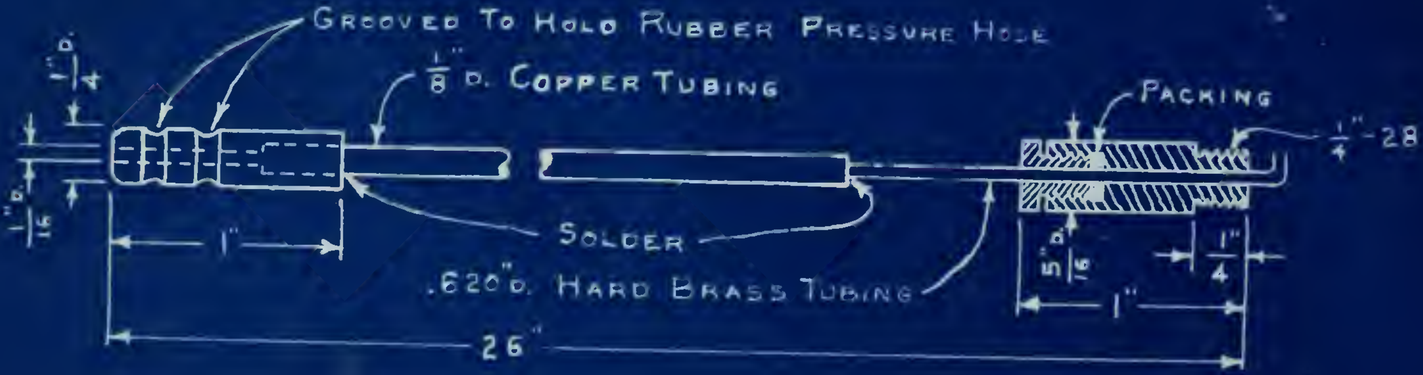


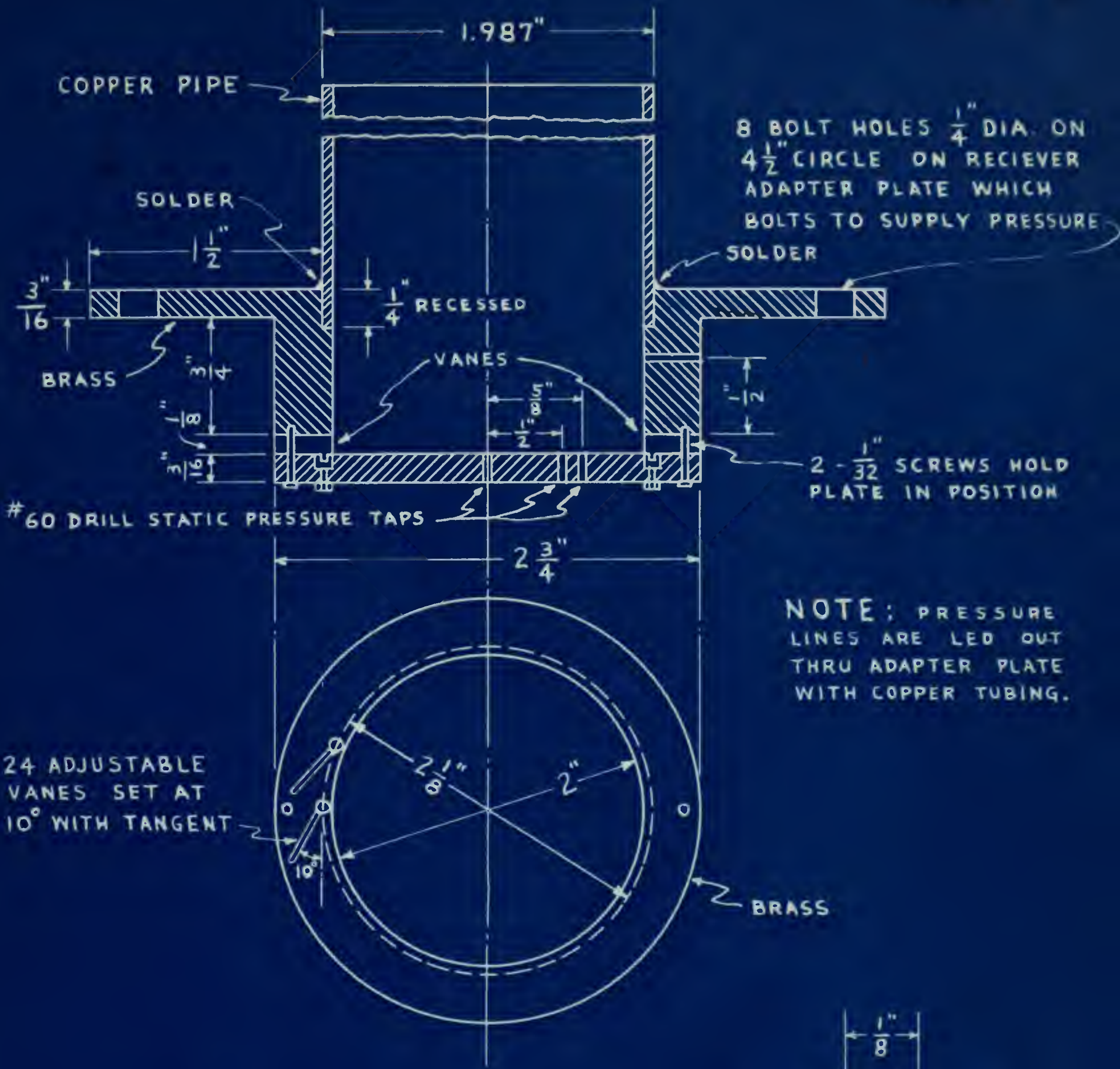
BRASS

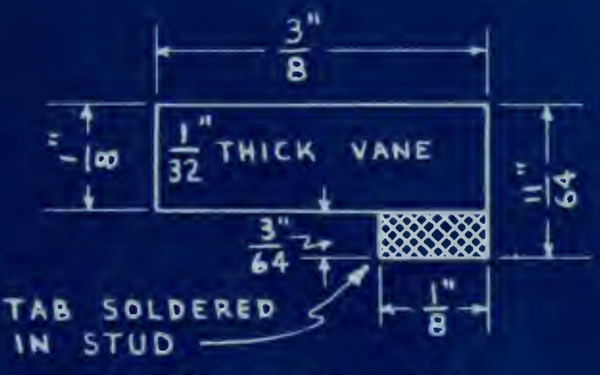
STATIC PRESSURE ADAPTER



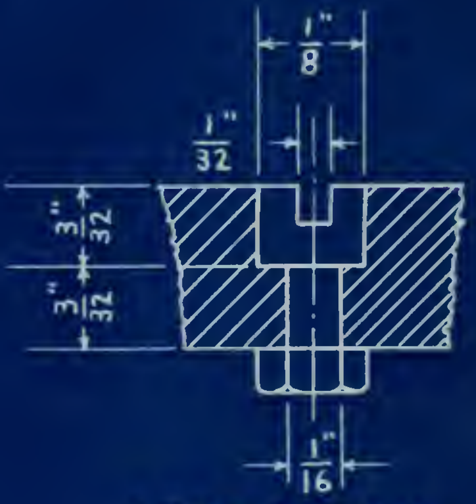
TOTAL PRESSURE ADAPTER




1.987"
COPPER PIPE
8 BOLT HOLES 1/4" DIA. ON 4 1/2" CIRCLE ON RECIEVER ADAPTER PLATE WHICH BOLTS TO SUPPLY PRESSURE
SOLDER
SOLDER
1 1/2"
3/16"
1/4" RECESSED
BRASS
VANES
3/4"
5/8"
1/2"
1/2"
1/8"
3/16"
2 - 1/32" SCREWS HOLD PLATE IN POSITION
#60 DRILL STATIC PRESSURE TAPS
2 3/4"
NOTE: PRESSURE LINES ARE LED OUT THRU ADAPTER PLATE WITH COPPER TUBING.
24 ADJUSTABLE VANES SET AT 10° WITH TANGENT
2 1/8"
2"
10°
BRASS



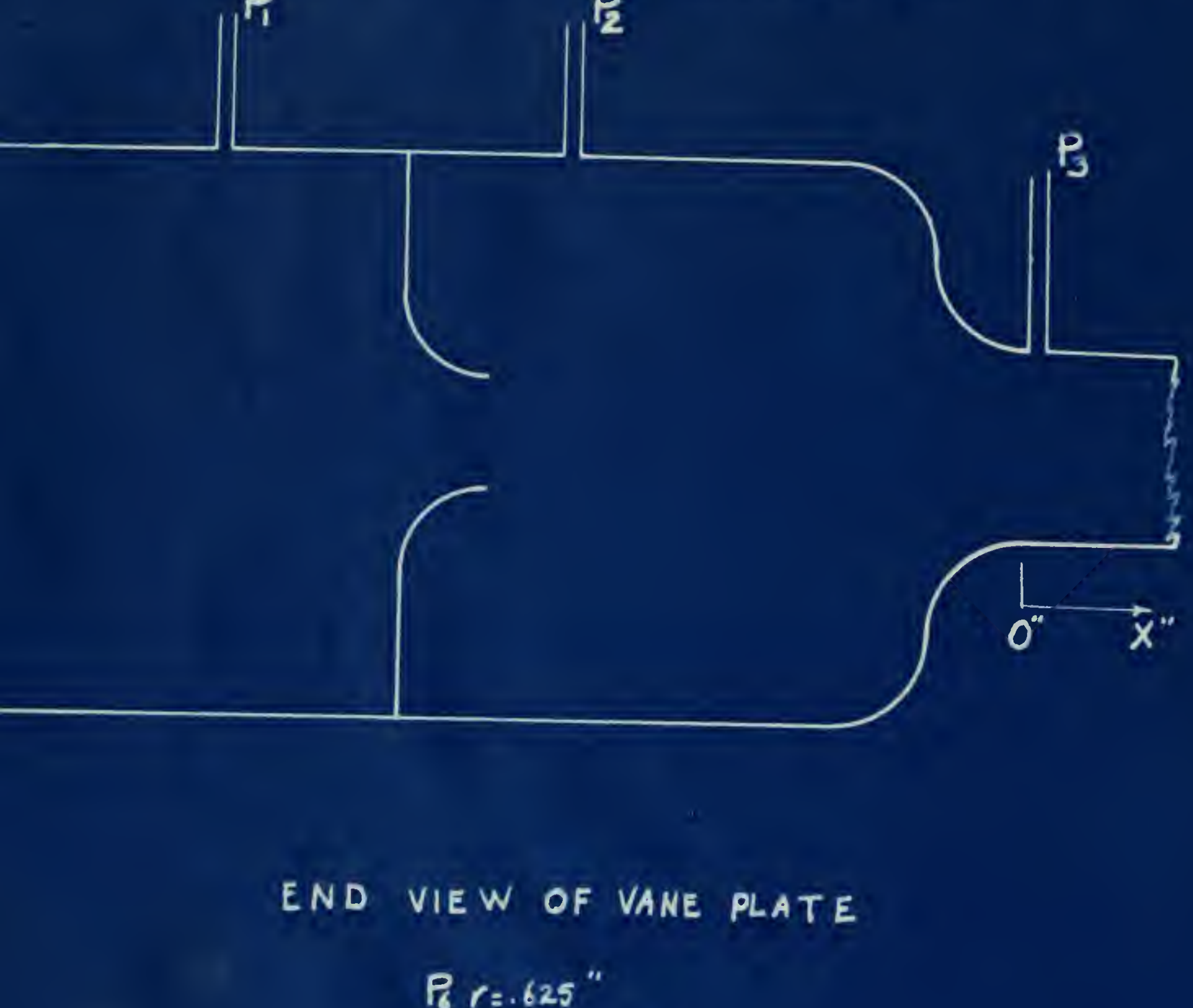
VANE DETAIL



STUD DETAIL

VORTEX VALVE

SCHEMATIC DIAGRAM
OF VANE INDUCED VORTEX VANE PLATE
INSTRUMENTATION



END VIEW OF VANE PLATE

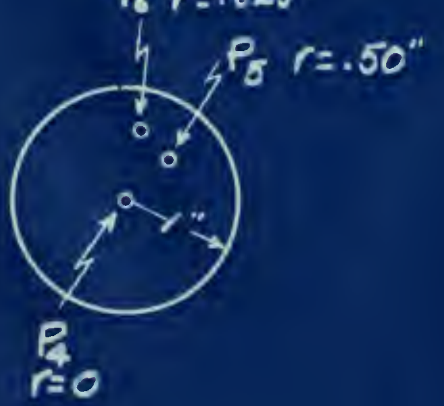


TABLE OF CONTENTS

OBJECT OF INVESTIGATION. 1

APPARATUS. 1

PRESENT DAY FREE VORTEX THEORY. 4

DISCUSSION OF RESULTS. 6

CONCLUSIONS. 14

SUGGESTIONS FOR FUTURE INVESTIGATIONS. 15

TABLES NUMBER ONE THRU NINE. 17-24

RING FORMATION PHOTOGRAPH. 25

CURVES NUMBER ONE THRU NINE. 26-34

PLATES NUMBER ONE THRU SIX. 35-40

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R4 Ricketts
Energy transformation
in a free vortex.

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